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***Advanced Mobile Phone Service:***

# The Cellular Test Bed

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*The Cellular Test Bed is a comprehensively instrumented field test laboratory supporting the development and evaluation of the Advanced Mobile Phone Service* (AMPS). *It consists of three main cell sites and six co-channel interferer sites configured in a small-cell hexagonal grid centered on the Newark, N.J. area. The sites interface with a central control and monitoring facility that incorporates a miniprocessor and related peripherals. A highly instrumented mobile laboratory performs fundamental data-gathering tasks and functions as the system mobile unit. A dedicated analysis facility is used to process and interpret the field-gathered data and simulate alternative operating system algorithms and their effect upon performance.*

## I. INTRODUCTION

Bell Laboratories is engaged in an ongoing field studies program to characterize the performance of UHF cellular mobile telecommunications systems. This program, designated the Cellular Test Bed (CTB) in its present phase, evolved from fundamental investigations of propagation-related phenomena. The initial thrust of the field studies program was to expand the work of previous investigators in order to generate a modeling of the influences of tbe environment on UHF signal propagation between a land site and mobile unit. To accomplish this modeling, a specially instrumented vehicle and land transmitting stations were developed and installed in the Whippany, N.J. and metropolitan Philadelphia, Pa. areas to provide UHF signal propagation data. The stations were located in a variety of propagation environments typical of suburban and urban communities so that conclusions drawn from the data are applicable to the broad deployment requirements of a practical cellular system.

Specifically, in the first phase of the field experiments, statistics were generated on UHF path loss as a function of range, propagation environment, and antenna elevation. The tests furnished data to characterize environmental noise and the correlation properties of signals received at the mobile unit from transmitting antennas at widely separated land sites. The results of these early experiments supplied the information necessary to specify system radio-plan parameters affecting radio coverage and frequency reuse.

A second phase of the field program emphasized the evaluation of specific antenna designs, equipment, and radio plan functions basic to the successful operation of high-capacity cellular systems. Field testing included data gathering on polarization and space diversity, vehicle location by signal strength and time delay, antenna gain and directivity, high-speed signaling, and voice transmission. These data have formed the basis for the development of cellular system control algorithms, particularly those related to vehicle location and handoff, and the performance specification of the radio transmission equipment.

The third and current phase of the program is structured to provide system-level evaluation of a broad class of cellular radio plan designs. The field configuration used for this effort, the CTB, consists of three main cell sites and six co-channel interferer sites installed in a small-cell hexagonal grid centered on the metropolitan Newark area. A primary objective of the CTB is the technical demonstration of small-cell interference-limited system operation.

The important features of the CTB test instrumentation and analysis facilities are:

(*i*) The data base is generated in a field environment using all the essential features of a small-cell radio plan configuration.

(*ii*) The instrumentation incorporates data-gathering facilities that permit the generation of a comprehensive, high-resolution data base, which can be used to design and evaluate system control algorithms.

(*iii*) The analysis facilities provide for fast turn-around data validation and fully utilize the field instrumentation capability to develop performance results.

These features ensure that data gathered in the CTB are reliable, reproducible, and statistically consistent with the objectives of each test sequence.

## II. CTB OBJECTIVES

Efficient spectrum management of cellular systems such as AMPS requires the effective application of many interrelated system control algorithms. These algorithms are used to process inputs such as received signal measurement data and, on the basis of assumed prop-

agation models, generate control decisions. The algorithm operation was developed and studies were performed using computer simulations that rely upon a statistical modeling of the propagation environment. The corresponding circuit functions were evaluated with hardware simulations of the radio transmission path. The CTB extends laboratory and computer simulation results by characterizing, in the field environment, basic operating sequences of the cellular radio plan and evaluating their influence on the quality of service.

The limited tests performed in the laboratory are extended in the CTB to incorporate hardware, software, and environmental interaction effects that are not well understood or anticipated. Consequently, final confirmation that circuit performance is predictable and proper comes from the live field environment. Similarly, the CTB provides a reference calibration for system-level performance simulations obtained by computer modeling. Computer-generated simulations are inherently well suited to evaluate effects of parameter perturbations and to extend simple system models to more complex configurations; the CTB provides a field reference to establish the validity of the basic models and enables proper interpretations of simulation results derived in modeling more sophisticated system configurations.

The CTB instrumentation, therefore, is designed to provide data on cellular system performance at two extremes of system complexity. The noise-limited system plan is studied in a three cell-site, omnidirectional antenna configuration; the small-cell interference-limited system plan is evaluated under the influence of a complete set of cochannel interferers in a directional antenna configuration. The latter arrangement stresses full frequency reuse, characteristic of the mature form of AMPS.

In both these equipment configurations, CTB data characterize system performance parameters, among which are the distributions of carrier-to-noise ratio (CNR) and carrier-to-interference ratio (CIR) over the cellular coverage region. Since these signal, noise, and interference relationships have a direct correspondence to voice quality and signaling reliability, they provide a first-order measurement of how closely system design objectives are being met.

Evaluations of signaling performance under dynamic field conditions are also of fundamental significance to the successful operation of AMPS. CTB-collected data relate transmission errors to the observed CNR and CIR distributions, to vehicle speed influences, to terrain characteristics, and to man-made noise effects.

Additional system functions tested in the CTB include vehicle-locating algorithms and voice channel handoff among cell sites. The frequency of handoffs, the location within the cell where handoffs occur most often, the improvement in CNR and CIR following handoffs, and the adequacy of locating decisions are all precisely characterized for

comparison with results achieved in simulations. Such comparisons provide a reference which serves to qualify and build confidence in system-simulation modeling.

The CTB must furnish performance evaluations which are easily interpreted and which, therefore, minimize the time needed for subsequent analysis at the system level. This capability has been incorporated through the minicomputer/microprocessor technology used to control tests, collect data, and perform preliminary processing. This technology makes it possible to simultaneously meet the seemingly contradictory objectives of rigorous performance characterization and timely engineering-level data interpretation.

## III. CONFIGURATION

The Cellular Test Bed site configuration (Fig. 1) has three centrally located cell sites for radio coverage of the Newark, N.J. area, and six

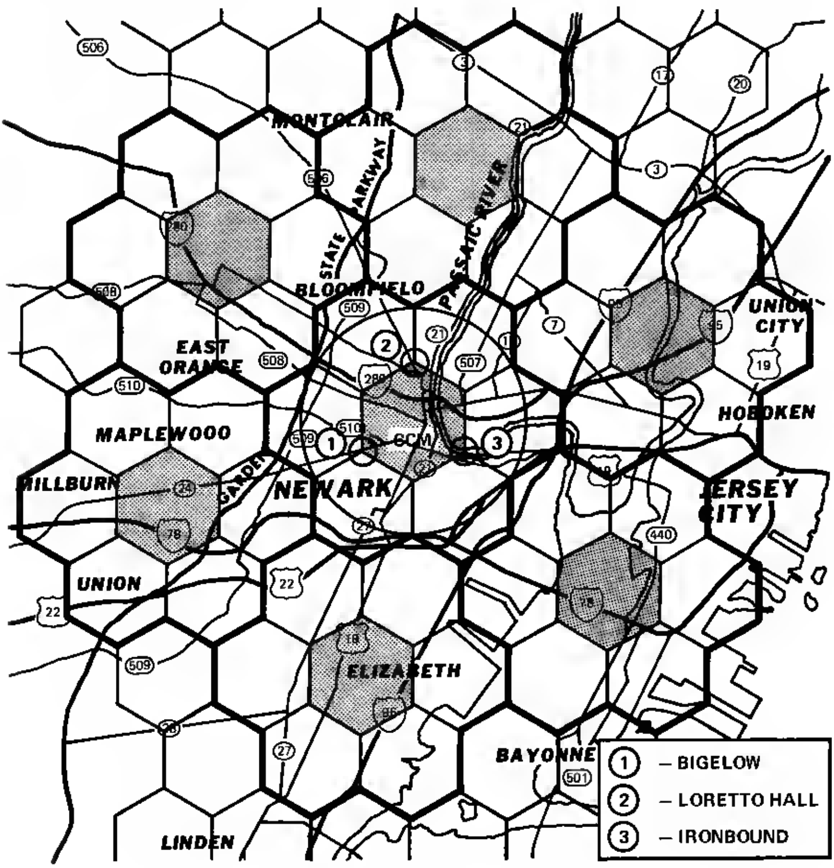


Fig. 1—Cellular Test Bed site configuration.

appropriately located remote transmitter sites for co-channel interference in the central coverage region. All sites are equipped with directional and omnidirectional antennas to permit the evaluation of both AMPS radio plan geometries. The sites can be power-controlled to simulate other radio plans. In the directional mode, the central sites provide corner-excited coverage of a single hexagonal cell, 1.4 miles in radius, and partial coverage of the six adjacent cells. In the omnidirectional mode, the same sites provide center excitation of three separate cells.

The six co-channel transmitter sites are located 4.6 cell radii from the central cell. Each CTB co-channel site simulates the interference generated by the three sites serving the particular co-channel cell by means of a power-control algorithm which accounts for antenna directivity and height, terrain, site location, and channel occupancy. The main and co-channel sites interface via voice and data land lines with a Central Control and Monitoring (CCM) facility located in central Newark. The CCM site emulates the algorithmic processing and radio plan control functions of an Electronic Switching System (ESS) in AMPS. It also contains the facilities necessary to acquire and record the collected data base.

The CTB "mobile" (Fig. 2) is a specially instrumented test vehicle designated the Mobile Communications Laboratory (MCL). It is equipped with the transceiver and control facilities necessary to perform the required operating and data-gathering tasks. Data acquired by the MCL are processed, formatted, and transmitted to a centrally

Fig. 2—Cellular Test Bed mobile—Mobile Communications Laboratory (MCL).

located telemetry site via radio link and then sent on to the CCM site via land lines. These radio and land links, in addition to the cell site links, permit essentially all measurement data, including the mobile data, to be acquired and stored on a common digital magnetic tape at the CCM. Additionally, audio generated at the CCM using specially calibrated analog recordings, is carried by land lines to the "serving" cell site where it is transmitted for recording at the MCL.

This CTB configuration is sufficiently flexible to test the radio plan and control algorithms for a number of system configurations that are of interest. By means of power control scaling, the CTB simulates various cell sizes and co-channel separation distances to permit evaluation of each stage of AMPS growth and study of other radio plan alternatives.

## IV. DATA RECORDING

The design philosophy of the field instrumentation allows flexible use of the field components to emulate both noise and interference-limited system performance. Accordingly, the hardware and software are designed to accommodate the broad spectrum of operational algorithms proposed to control and manage a mature cellular system. To accomplish this, the field configuration incorporates data-gathering and performance-monitoring functions that offer the analyst all the data resolution necessary to quantify the performance of system-level control of each operational event. For example, it is expected that in AMPS a system control algorithm will sample the signal strength received from each off-hook mobile in the service area once every few seconds. So that the Cellular Test Bed can acquire the additional signal strength data necessary to evaluate the effectiveness of such periodic interrogations, capability is incorporated within the MCL and at each cell site to sample signal-strength information once every one-half second. The one-half second interval serves as the basic CTB data-acquisition frame for all data recording.

The cell site data-acquisition system sequentially samples, at a 512-Hz rate, the signal received from the mobile on all eight cell site receive antennas. These samples are averaged by the cell site processor to produce eight one-half second means of the signal strength, based on 64 samples each. Each mean value and the last instantaneous sample contributing to that mean are transferred to the CCM every data frame.

The MCL data acquisition system provides a more comprehensive RF data record since it performs more than 3300 measurements during the equivalent one-half second interval. On the basis of these measurements, the MCL establisbes and transmits to the CCM the following radio transmission parameters for each data frame:

(*i*) Mean received cell site setup channel carrier level from each of the three central cell sites.

(*ii*) Mean received cell site voice channel carrier level from the serving cell site.

(*iii*) Mean received interferer carrier level from each of the six interferers.

(*iv*) Mean mobile-received noise.

(*v*) Peak mobile-received noise histogram.

This microscopic data gathering and recording takes place concurrently with the execution of the system control operational algorithm under test. Similarly, all system status parameters, including those related to mobile-unit performance, are measured and recorded every one-half second. Such a data base enables system-control algorithm performance to be thoroughly evaluated and developed to maturity.

More specifically, the instrumentation data collected in CTB are grouped broadly into four categories which quantitatively characterize (*i*) radio frequency transmission, (*ii*) the performance of system control algorithms, (*iii*) the performance of specific system functions, and (*iv*) the performance of the data acquisition system; the latter data serve to qualify and aid the interpretation of the other three data categories. The data are further classified according to source: mobile or land-originated. Table I lists representative examples of each data category and identifies its source.

As described below, the data are collected from both instantaneously sampled and real-time processed events. The instrumentation data collected in the CTB include 30 instrumentation words from the MCL and 24 words of data from each cell site. To accomplish this, 102 words of instrumentation data are recorded during each one-half second of real time.

In addition, operational status, self-check results, and data from the

Table I—Representative examples of data categories and sources

| Data Category | Source |
|---|---|
| 1. Transmission Data: | |
| Carrier amplitude | Mobile and land |
| Average and impulsive noise | Mobile |
| Co-channel signals | Mobile |
| Locating signals | Land |
| 2. Algorithm Data: | |
| Location estimates | Land |
| Handoff events | Land |
| Cell site/mobile traffic distribution | Land |
| 3. System Function Data: | |
| Signaling performance | Mobile |
| Voice transmission | Mobile |
| Diversity | Mobile |
| 4. Operational Data: | |
| Time references | Land and mobile |
| True vehicle position | Mobile |
| Control flags | Land |
| Bookkeeping data | Land and mobile |

system control process are added to complete the data package. The full complement of data constitutes a 204-word record of information recorded every one-half second.

## V. IMPLEMENTATION

The comprehensive data base described above is obtained from measurements using specially designed land site and mobile data acquisition facilities. Specific equipment designs for these facilities are described below.

### 5.1 Central cell sites

The radio coverage plans proposed for AMPS require the use of both omnidirectional and directional antennas. Consequently, each of the CTB central cell sites uses 12 antennas (three 6-dB* omnidirectional antennas and nine 8-dB directional antennas) to evaluate the coverage algorithms. An additional omnidirectional antenna is used at each site for test control. The composite antenna array, illustrated in Fig. 3, is

* Relative to one-half wavelength dipole reference antenna.

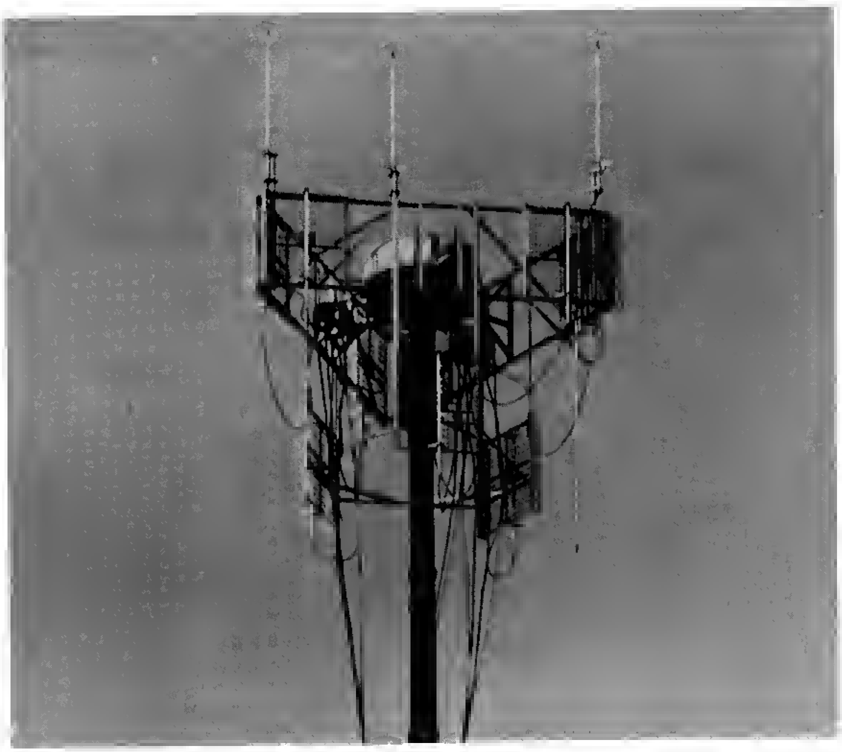

Fig. 3—Cell site antenna array.

supported approximately 100 feet above the local street surface by a free-standing Corten* steel mast at two of the cell sites and by a roof-mounted 50-ft mast at the third site. Each mast has a winch and an internal halyard assembly of three steel cables for raising and lowering the antenna frame from the ground to facilitate antenna and transmission cable servicing.

Two of the three omnidirectional antennas are appropriately spaced for diversity reception of the mobile unit transmission; the third is assigned for cell site transmission. Three directional antennas serve each of the three 120-degree sectors (or faces) surrounding the site. Two directional antennas, appropriately spaced, are used to achieve diversity reception for the face they serve; the third directional antenna is used for cell site transmissions. Figures 4 and 5 illustrate typical radiation patterns of the CTB antennas.

Each antenna in the array is coupled to the cell site equipment through a 150-ft, ⅝-in.-diameter, 50-ohm, semirigid cable having a

* Registered trademark of the U.S. Steel Company.

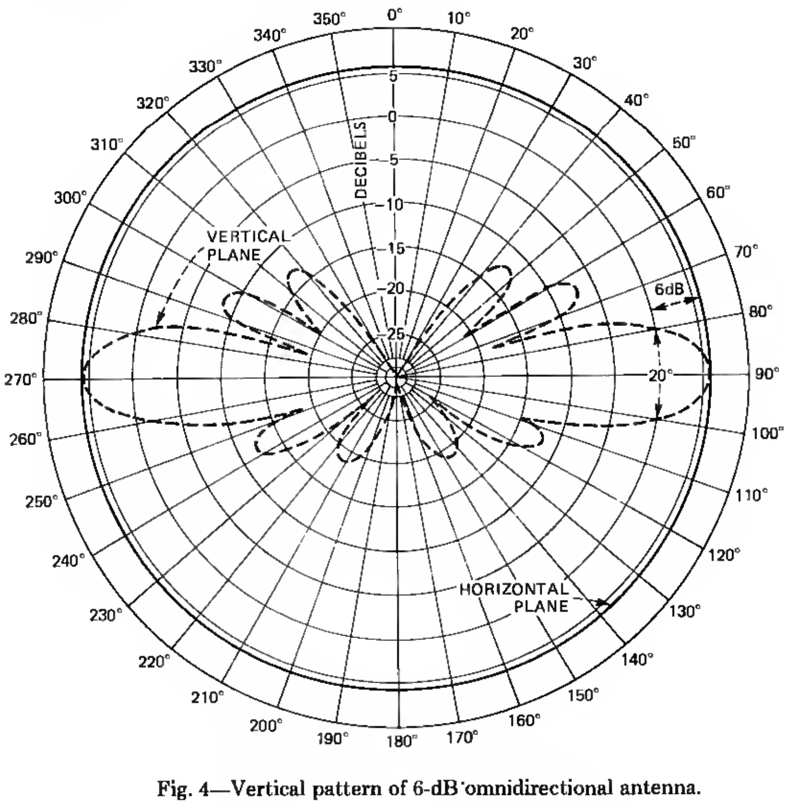


Fig. 4—Vertical pattern of 6-dB omnidirectional antenna.

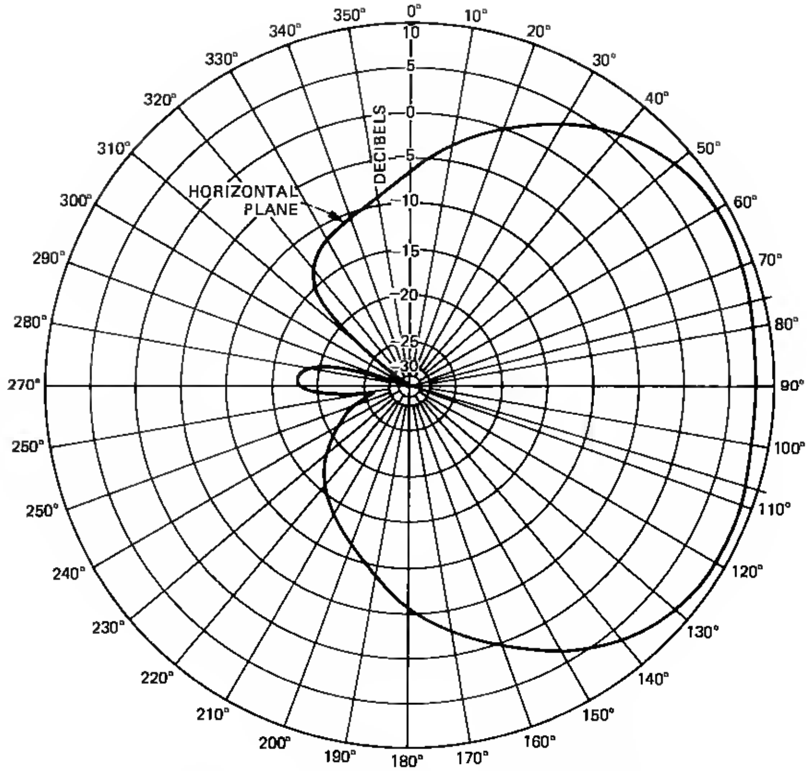


Fig. 5(a)—Azimuthal pattern of 8-dB directional antenna.

nominal RF transmission loss of 0.03 dB per foot at 850 MHz. The return-loss performance of the antenna, transmission line, and connector assembly is maintained at ≥15 dB.

The four transmit antennas are excited by the cell site configuration shown in Fig. 6. Two independent radios service omnidirectional operation; two additional independent radios service directional operation. Each transmit radio path includes a UHF variable-power amplifier, which can produce up to 10 watts at its corresponding antenna terminals, and the two radios servicing the directional antennas can transmit on any of the three cell site faces—A, B, or C.

The receiver configuration of the three central cell sites, shown in Fig. 7, is more complex. Two receive antennas are used to achieve diversity reception on each radio channel in service and, as in the transmit case, each radio serving the directional antennas can be switched to service any of the three cell site faces. Basic to the cell site operating and data-gathering architecture is the instrumentation receiver, which has been designed to satisfy, concurrently, the operating

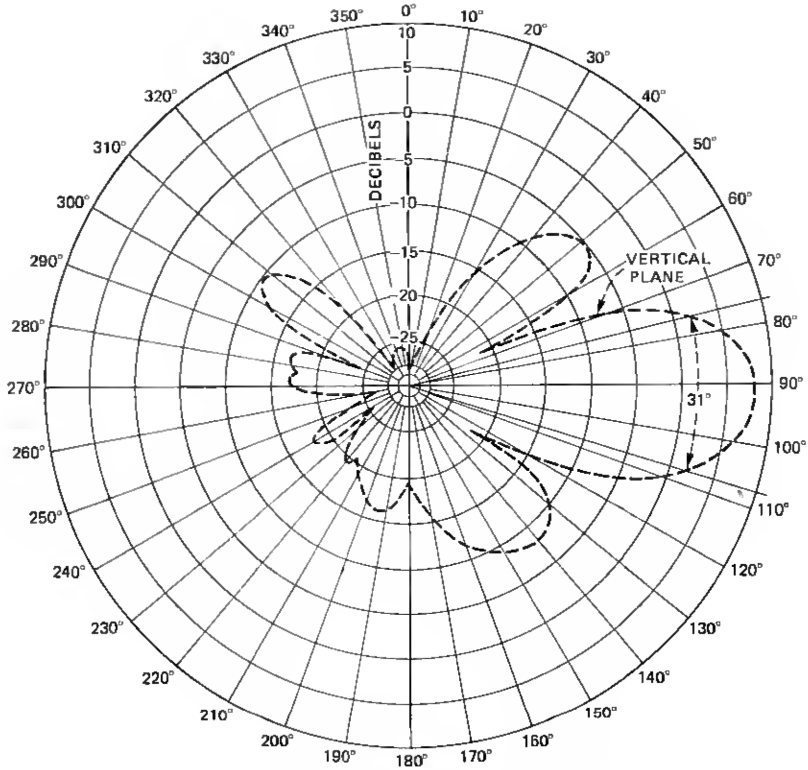


Fig. 5(b)—Vertical pattern of 8-dB directional antenna.

algorithm under test and the CTB's data-gathering requirements. At a 512-Hz rate, the receiver switch shown in Fig. 7 electronically sequences through all eight cell site receive antennas. The signal strength from each antenna is sampled to form a one-half second mean, which is calculated by the programmable controller (PROCON) and sent to the CCM site. The CCM requests, receives, and records such information from all three main cell sites every one-half second. All information recorded is tagged to identify the time of the measurements and the particular radio/antenna combination and cell site in use.

As mentioned above, a PROCON is embedded within the control architecture of each central cell site; it responds to command and interrogation messages sent by the CCM via conventional land lines and Western Electric 201 data set facilities. The cell site PROCON is interfaced to peripherals that enable it to perform data acquisition, data processing, and equipment calibration and surveillance functions consistent with cell site evaluation and data-gathering requirements.

To facilitate field modification of both the configuration and test

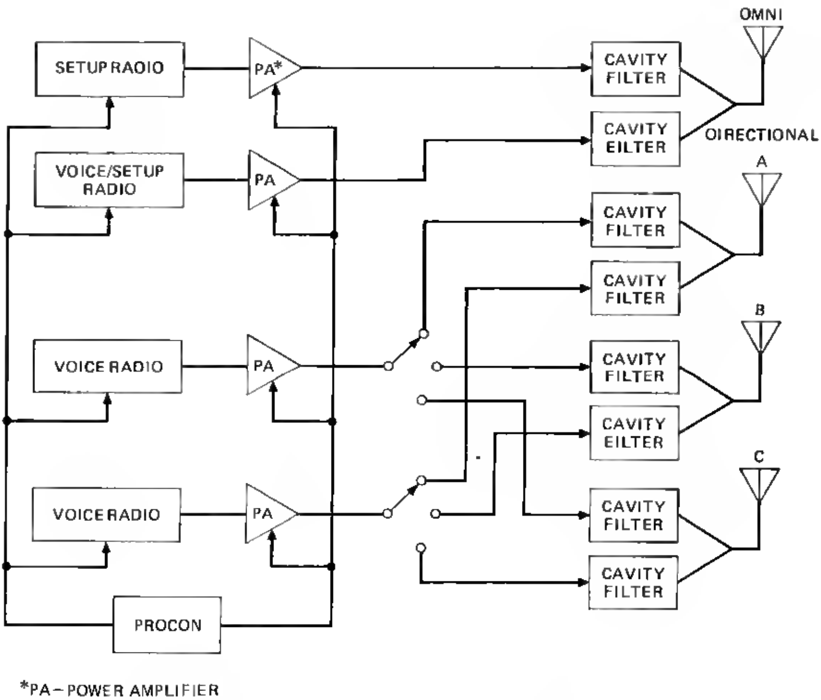


Fig. 6—Cell site transmitter configuration.

operations requirements, the PROCON at each site can be reprogrammed remotely from the CCM.

### 5.2 Co-channel sites

Since the co-channel sites need not perform system receive and data-acquisition functions, they have a much simpler transmission architecture than the central cell sites. Figure 8 shows that the interferer architecture includes two cell site radios with transmit functions only. These radios drive power amplifiers whose outputs are attenuated as required and are then hybrid-coupled to an omnidirectional antenna and a directional antenna. The radios can be modulated with either a voice signal originating at the CCM or a data signal supplied by a local signaling subsystem. The equipment control functions are administered by an eight-bit microprocessor that interfaces with the CCM via telephone data lines.

During field evaluation operations, both transmitters are active. One supplies the interference signal at the radio frequency used by the "serving" central cell site. The second transmitter generates a carrier signal at a frequency unique to the particular co-channel site. The MCL, therefore, acquires signal strength data on the composite inter-

ference generated by all six co-channel sites and the interference unique to each site.

### 5.3 Central control and monitoring site

Figure 9 illustrates the system design of the CCM, which is based on an HP 2100 miniprocessor data-acquisition system. Through software, it emulates radio plan control functions performed by an ESS, supervises data gathering and recording, and automatically calibrates and monitors the performance of all the Cellular Test Bed's land-based radio components. The CCM interrogates and instructs the mobile unit via telemetry link and the cell sites via specially conditioned land lines. Operator intervention, if needed, is also available. The cell site control message formats, as in the AMPS design, include seven parity bits to ensure high reliability of data transmission. The CCM software requests data retransmission whenever errors occur. The CCM also contains the calibrated audio facilities necessary to conduct voice quality tests.

### 5.4 Telemetry site

The telemetry site (TM) incorporates the radio transceiver facilities, which permit the CCM to reliably instruct and interrogate the MCL anywhere within the CTB test probe area. To meet the transmit/receive path reliability requirements of this important radio link, the TM site is centrally located within the probe area and uses a high-gain transmit and diversity-receive antenna system elevated 230 feet above the local street surface. The TM site also incorporates voice communication facilities to administer field test operations.

### 5.5 Mobile communications laboratory

The interior of the MCL (see Fig. 10) contains radio, logic, miniprocessor, and data-recording facilities. The RF/analog subsystem, which consists of five measurement channels driven by two electronically selectable RF preamplifiers fed from two receive antennas appropriately spaced for diversity reception, is illustrated in Fig. 11. The same antennas and preamplifiers also feed the AMPS mobile radio used to evaluate the performance of the voice and signaling subsystems.

The main measurement receiver uses a computer-controlled agile local oscillator, which mixes the RF signals down to three intermediate frequencies. Each of these frequencies feeds into two highly selective channels that use logarithmic detectors. Two channels (one high-gain, one low-gain) service each IF signal to achieve an instantaneous dynamic range that is linear from −150 to −30 dBm. The two channels are adjusted to maintain a 20-dB overlap centered at −90 dBm. The measurements for calculating real-time average values are selected using either the high-gain measurement or by accepting the low-gain

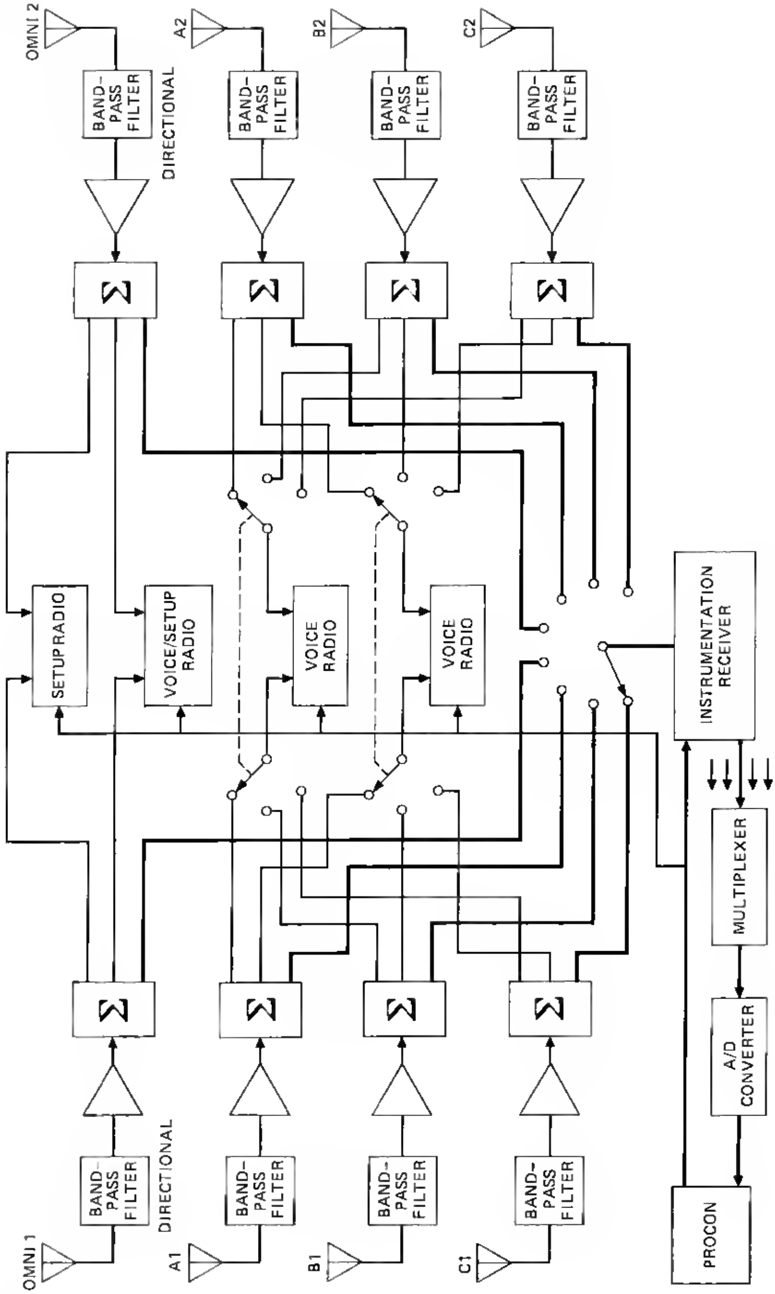


Fig. 7—Cell site receiver configuration.

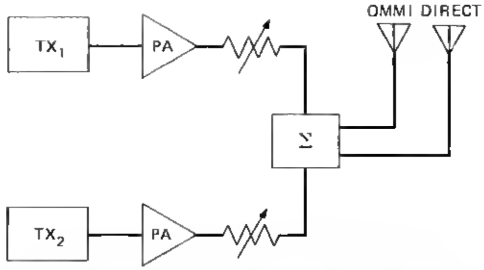


Fig. 8—Co-channel cell site transmitter configuration.

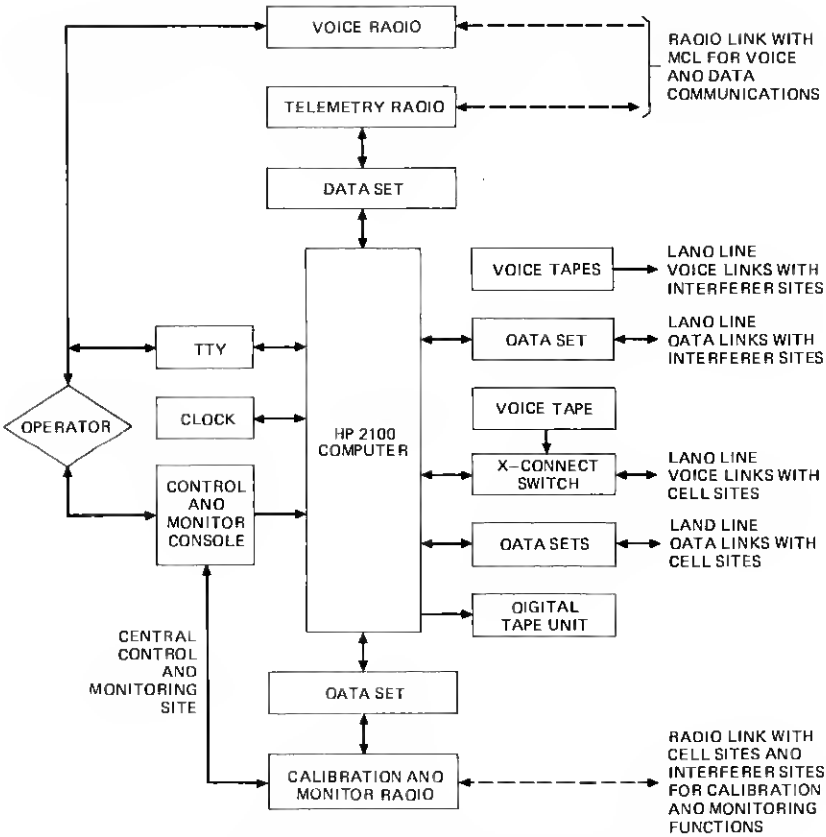


Fig. 9—Central control and monitoring facility.

result if it exceeds a threshold approximately in the middle of the overlap region.

Environmental noise is monitored on one antenna by a single logarithmic detector with a linear range from −150 to −70 dBm. The output of the diversity switch in the mobile radio is measured by an eighth logarithmic detector having a linear range from −120 to −40 dBm, with the useful range extending nearly 10 dB more at each end.

Fig. 10—Mobile Communications Laboratory interior.

Instantaneous data sampled from these receivers are processed to obtain a true incident power by a stored program reference tabulation. This processing translates the output from a 10-bit analog-to-digital converter to a number proportional to the corresponding instantaneous input signal power. The instantaneous signal power samples are summed over one-half second of real-time to calculate average values.

The MCL is also equipped with a gyroscopic-bearing and distance-tracking system so that all system status and measurement information recorded each one-half second are tagged with true vehicle position.

### 5.6 CTB calibration and performance monitoring

The calibration and performance-monitoring equipment in the CTB's hardware and software designs and the subsequent off-line statistical processing of the measurement data can precisely control and qualify the field experiments to obtain results comparable in resolution and reliability to those achieved in the laboratory. Examples of the calibration and performance monitoring subsystems incorporated within the central and interferer cell sites are shown in Figs. 12 and 13. The MCL uses a similar calibration and monitoring system.

The cell site transmit calibration and monitoring subsystem monitors, via precision coupler and temperature-compensated detection circuits, the RF power incident to and reflected from each antenna/cable assembly (see Fig. 12). The detected voltages, sampled and processed by the PROCON, are sent to the CCM, where they are monitored and recorded (on-line) to insure the integrity of the cell site transmit function.

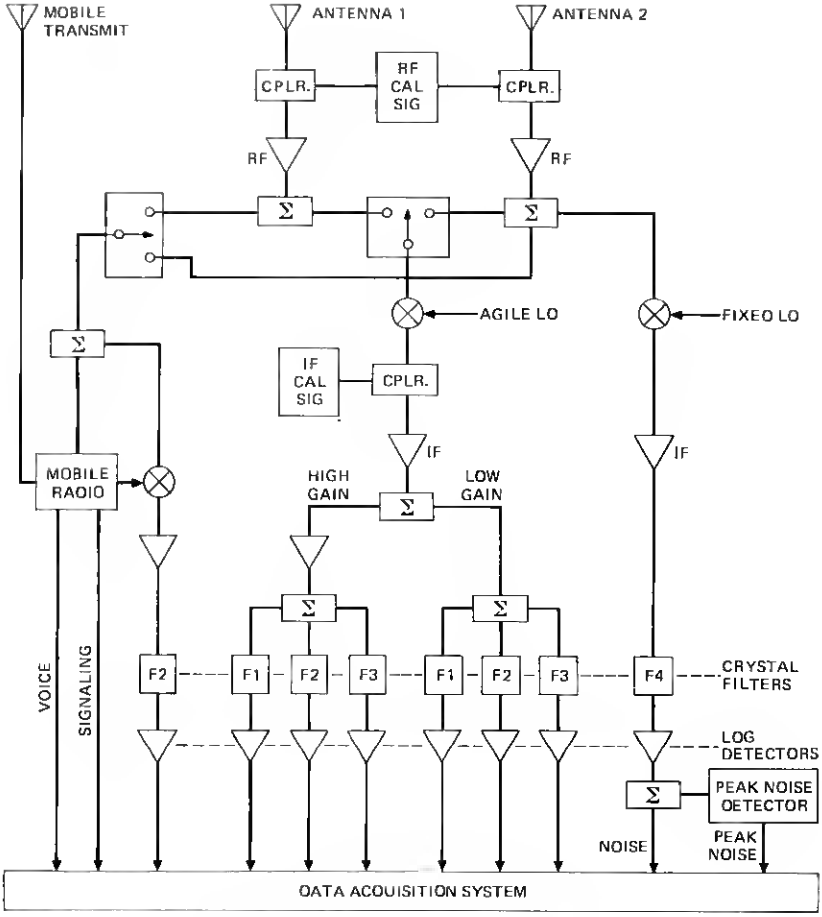


Fig. 11—MCL RF/analog subsystem configuration.

The type of calibration and monitoring subsystem used in the cell site receivers is illustrated in Fig. 13. In practice, the test generator is set, under CCM control, to a reference power level. The CCM then (via land lines and the PROCON) automatically steps a programmable, precision attenuator to supply the input reference signals necessary to calibrate the cell site instrumentation receiver over its entire 80-dB dynamic range. At each reference level, 1000 samples are taken and averaged to generate stored program reference tabulations which, during real-time data acquisition, are used to determine the true instantaneous signal strength incident at the terminals of the receive antenna. The test generator also furnishes a reference signal to each antenna and cable subsystem. The instrumentation receiver monitors the forward and reflected power to ensure that antenna system return-

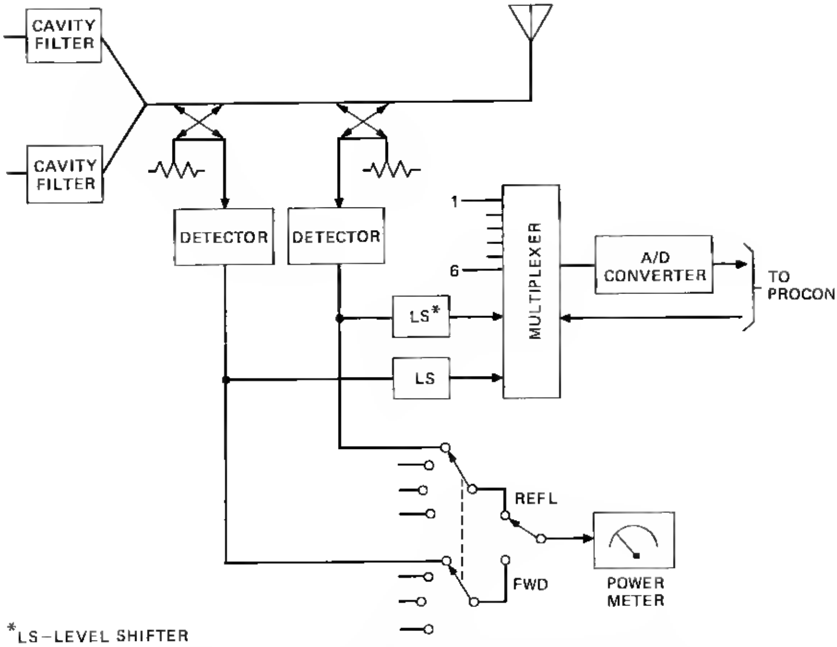


Fig. 12—Cell site transmitter calibration subsystem.

loss requirements are met. As shown, the test generator subsystem also furnishes the reference signals necessary to establish the FM quieting performance of the AMPS radios. Calibration of the CTB's transmit-and-receive subsystems is maintained within ±½ dB during each field evaluation sequence. The calibrations are performed at least before and after each test sequence and are hardcopied as part of the data package.

## VI. CONTROL/RECORDING ARCHITECTURE

This section describes the system control and data-recording structures of the CTB that perform the AMPS emulation and data-acquisition functions. As noted previously, an extensive data base of transmission parameters is established at the CCM every data frame. The algorithmic software module accesses the appropriate cell site transmission data at programmed intervals and makes system control decisions, which are communicated to the cell sites and implemented by the operating system. The following paragraphs discuss the communication, control, measurement, and data-recording aspects of CTB operation.

### *6.1 CTB data communication*

As described earlier, the CTB field experiments are administered through the CCM, which is linked with cell sites by data lines and to

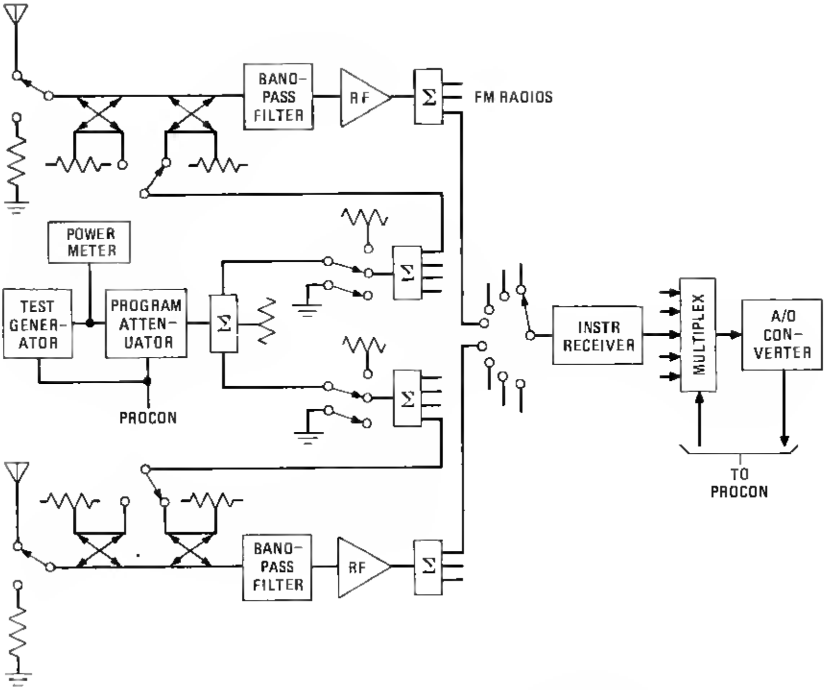


Fig. 13—Cell site receiver calibration subsystem.

the MCL by a full-duplex telemetry channel. These interconnections, together with powerful processing capability at each remote site, form a comprehensive data communications structure.

Basically, three types of messages are used for data communications within this field configuration: First, control messages, such as signaling requests to cell sites, permit the execution of system-level operations. Second, special data acquisition requests and data messages to and from cell sites and the MCL permit the acquisition of data at the CCM. Third, CTB operational-control messages permit the automatic calibration of cell sites, synchronize the data-acquisition frame at each cell site and the MCL, control interferer site power and frequency, and provide status information on the proper performance of the system. The last category of messages allows direct CCM instructions to the mobile logic unit via telemetry link and also permits the MCL and CCM operators to request test pauses.

The land-line messages are transmitted at a rate of 2400 b/s, while the MCL data transfer rate is 1800 b/s. All messages are formatted into 32-bit blocks with seven bits devoted to error control. The data are encoded in a shortened (127, 120) Bose-Chaudhuri-Hocquenghem (BCH) code, which is used in an error-detection mode with retransmission.

### 6.2 System control

The CTB configuration must be properly initialized to start data acquisition. First, the interferer transmitters and the main cell site instrumentation receivers must be tuned to the serving channel. Then the test can start by synchronizing the data-acquisition frames at each cell site and the MCL with the CCM system clock. From that point on, microscopic data measurements at the MCL and cell sites depend on their local clocks. The CCM data-collection subsystem initiates each frame with a "request-for-data" message to the cell sites and the MCL. The data received are checked and formatted by a CCM software module and placed in a buffer to the system-control algorithmic module. This module is coded so that it can access data available to the AMPS control algorithms only at the proper time intervals. The output of the module may request a system reconfiguration, which is accomplished by the CCM with appropriate data-link messages. All system decisions, requests for action, and actions are recorded with the underlying data for later analysis.

### 6.3 Measurement of RF transmission parameters

Radio transmission parameters are measured at each of the cell sites and at the MCL. Each cell site instrumentation receiver switches sequentially to each of eight RF channels (Fig. 7) for sampling the mobile carrier level as received on each of two omnidirectional and three pairs of directional antennas. The data-sampling rate is 512 Hz, enabling the acquisition system to make 64 measurements per channel each data frame. The samples are processed through a calibration stored-program reference tabulation to generate quantities proportional to the RF signal as received at the antenna terminals. The cell site programmable controller then forms eight averages from these samples every data frame. If we assume an underlying Rayleigh distribution, these averages estimate the local means within a 95-percent confidence interval of approximately 1 dB. These eight averages together with the final eight instantaneous samples form the RF parameter list, which is transmitted to the CCM every data frame and recorded on digital tape in the format shown in Table II.

### 6.4 MCL activities

The MCL is a highly sophisticated data acquisition facility. As discussed in Section V, its five basic measurement channels are alternately switched to two diversity-receiving antennas. Further, measurements are made on both the high- and low-gain IF channels with the MCL computer selecting the proper value in real-time. Measurements are made on setup, voice, interferer, and noise channels. In addition, the AMPS diversity signal and peak-noise distribution are measured.

Table II—CCM data tape format—frame record

| Word | Description |
|---|---|
| 1 to 10 | CCM operational data |
| 11 to 14 | MCL operational data |
| | MCL measured data: |
| 15 | Serving channel diversity mean signal strength |
| 16 | Serving channel mean signal strength |
| 17 to 22 | Interferer 1 to 6 mean signal strength |
| 23 to 25 | Setup channel mean signal strength—3 cell sites |
| 26 | Noise mean |
| 27 to 32 | Peak noise histogram |
| 33 | Supervisory tone status |
| 34 | Serving channel |
| 35 | Mobile power status |
| 36 | Order |
| 37 | Standard deviation on serving channel signal strength |
| 38 to 48 | Signaling related data; voice and setup channels |
| | Cell site measured data: |
| 49 to 65 | Mean and instantaneous received signal strength—cell site 1 |
| 66 to 68 | Reserved |
| 69 to 77 | Cell site 1 supervisory tone transmitted power and other status reports |
| 78 to 93 | Mean and instantaneous received signal strength—cell site 2 |
| 94 to 97 | Reserved |
| 98 to 106 | Cell site 2 supervisory tone, transmitted power and other status reports |
| 107 to 122 | Mean and instantaneous received mobile signal strength—cell site 3 |
| 123 to 126 | Reserved |
| 127 to 135 | Cell site 3 supervisory tone, transmitted power and other status reports |
| 136 to 145 | Algorithm requests |
| 146 to 149 | Algorithm calculations (e.g., angle-of-arrival data) |
| 150 to 167 | Interferer channel and frequency assignments |
| 168 to 204 | CCM status flags |

Table III gives the fundamental MCL measurement sequence. As suggested, the sequence has 52 measurements with a data frame consisting of 64 repetitions of this sequence.

The MCL minicomputer processes the instantaneous data to obtain mean power estimates for every data frame. Each setup, voice, and interferer channel power estimate is based on 128 signal-strength samples since the contributions from both mobile diversity antennas are averaged together. Again, with a Rayleigh signal distribution, the averages estimate the mean power within a 95-percent confidence interval of approximately ¾ dB. Peak noise samples, which consist of 256 measurements per frame, are cast into a six-level histogram. The ranges are:

$$
\begin{aligned}
-93\text{ dBm} &< \text{range } 1 \\
-97\text{ dBm} &< \text{range } 2 \le -93\text{ dBm} \\
-101\text{ dBm} &< \text{range } 3 \le -97\text{ dBm} \\
-105\text{ dBm} &< \text{range } 4 \le -101\text{ dBm} \\
-109\text{ dBm} &< \text{range } 5 \le -105\text{ dBm} \\
-113\text{ dBm} &< \text{range } 6 \le -109\text{ dBm}.
\end{aligned}
$$

The instantaneous measurements are recorded on the digital tape unit at the MCL, while the CCM receives processed data in histogram form.

Table III—MCL measurement sequence*

| Measurement | Parameter |
|---|---|
| 1 to 12† | Setup channel signal strength—3 cell sites |
| 13 | Serving channel signal strength—diversity |
| 14 | Noise |
| 15 | Peak noise |
| 16 to 27† | Interferer 1–3 signal strength |
| 28 | Serving channel signal strength—diversity |
| 29 | Noise |
| 30 | Peak noise |
| 31 to 34† | Serving channel signal strength |
| 35 | Serving channel signal strength—diversity |
| 36 | Noise |
| 37 | Peak noise |
| 38 to 49† | Interferer 4 to 6 signal strength |
| 50 | Serving voice channel signal strength |
| 51 | Noise |
| 52 | Peak noise |

* Sixty-four measurement sequences constitute a data frame.

† These samples constitute measurements on both mobile receive antennas and on both low and high gain channels. The proper subset of these samples is selected by software.

The signal-strength data transferred to the CCM and recorded there consist of:

(*i*) Setup channels (three).
(*ii*) Interferer channels (six).
(*iii*) Voice channel.
(*iv*) AMPS receiver.
(*v*) Noise.
(*vi*) Histogram (six levels).
(*vii*) Standard deviation of voice channel signal power.

### *6.5 System function and algorithmic data*

The MCL with its versatile mobile logic unit monitors the performance of the signaling system. It reports the results of the paging scan, supervisory tone outages, and correctable as well as incorrectable data errors on the voice channel. By reporting to the CCM the state of the AMPS mobile (such as its operating channel), the MCL gives a direct measure of the performance of the AMPS signaling system.

The MCL uses an analog tape recorder to record the voice as received on the AMPS serving channel. Timing and event markers are also recorded on the audio tape to synchronize it with the digital data. This provides a complete record of performance and objective information on the AMPS serving channel.

The cell sites monitor and report to the CCM the status of the supervisory tone present on the serving channel. Also, as described previously, the cell sites report to the CCM the final instantaneous received signal-level measurements on the serving channel.

The AMPS algorithmic-software module, embedded within the CCM

operating system, accesses the instantaneous data each locating interval. On the basis of these signal samples, it makes handoff decisions, which are then implemented by the CCM operating system. The operating system records on the digital tape algorithmic level calculations, decisions, assignments (such as channel number and mobile power), and the results of their implementation, while the system continues its data-gathering functions.

### 6.6 Operational data

The operational data recorded in the CTB provide timing and MCL position information. Both the CCM and the MCL are equipped with crystal-controlled clocks supplying timing data with 20-$\mu$s resolution. The MCL timing data are transmitted to the CCM on the telemetry channel each data frame. The CCM-generated timing information is also recorded on digital tape. Using the calibrated position tracking system, the MCL's position is monitored each data frame and is known within tens of feet throughout a test.

Clearly, data acquired in the CTB must be reliable (or appropriately marked) to lead to valid performance evaluation. For this reason, online data on the state of the CTB are generated and recorded on the CCM digital tape. These data include trouble and status flags as described below.

If properly encoded data are not received at the CCM within the alloted time span (300 ms), a trouble flag is set to mark that event in the recorded data and a trouble report is issued on the CCM system console. An incomplete data package received at the CCM also causes a trouble flag and report. Once a complete error-free data transmission is received, the CCM validation routines examine the cell site signal-strength data for plausibility. If unreasonable measurement values are detected, the CCM sets a corresponding trouble flag.

Finally, the received signal-strength measurements are displayed in real-time on a graphics terminal. The test coordinator can request the display of any signal-strength measurement from each cell site. Unusual behavior in the displayed data is noted and may cause the test to be interrupted.

The AMPS locating-algorithmic program, which is resident within the CCM operating software, uses some of the cell site measured data to make required system handoff decisions. The algorithmic routine examines the aforementioned trouble flags and inhibits decisions when flags are set. If a handoff is deemed necessary, the algorithm requests new cell site and/or face and channel assignments from the operating system. This information is checked for plausibility and then stored and recorded on digital tape. Invalid algorithmic requests cause a trouble report to the system console and set a corresponding trouble

flag in the recorded data. Valid requests cause the operating system to issue the necessary instructions to the cell sites.

The MCL routinely sends the frequency of its AMPS operating channel to the CCM via telemetry. The CCM check routines, after accounting for response delays, compare the reported frequency of the MCL operating channel with that of the algorithm-assigned channel. In case of mismatch, a system reinitialization flag is set and recorded on tape, and a system-recovery process is initiated. The algorithm can also issue a system-restart request when a "lost mobile" condition occurs. This condition sets both the mobile status and the system reinitialization flags. On system reinitialization, the system software verifies the proper operational status of the cell site transmitters and measurement receivers. Improper operation is reported on the system console.

As part of the on-line monitoring system, the cell sites measure and report the RF output power of the transmitter to the CCM. This information is recorded on digital tape and is used on-line to alert the operator in case of a malfunction. The data are also collated and recorded within the 204-word block each data frame.

## VII. DATA PROCESSING

The basic objective of the CTB data acquisition and processing tasks is to quantitatively evaluate system performance and to present results in a form suitable for system-level engineering evaluations that will help determine the final AMPS design. Fundamental to such performance evaluations is the capability of generating high-quality results in a form that is easy to interpret. CTB data processing achieves this capability through a combination of "quick-look" status-assessment programs, data-validation programs, various data-reduction routines, special data-collecting and data-organizing techniques, and highly interactive graphic procedures for displaying results.

The quick-look software enables a first-cut, fast-turnaround process for examining the field-collected data, prior to complete processing, to gauge how well the experimental data conform to pretest expectations. These cursory results are used to provide feedback to the data-collection activities, adjust the experimental setup as appropriate, and fine-tune the test configuration to collect data under conditions most suitable to the test objectives.

The data-validation and data-reduction routines convert the raw field data into a form suitable for input to the analysis programs. During this process, certain data are identified for removal from the data base, as necessitated by limitations in CTB field hardware or software. These routines, in combination, perform the translation of bulk-recorded field data into information suitable for the evaluation and evolution of algorithms in subsequent analyses. The analysis and

display software provides data organization specifically matched to final-performance interpretations. These programs are further enhanced by a capability to reproduce the field experiment in the laboratory. The system-control algorithms can be modified and evaluated in a real-time simulation, which uses the raw field data as its input and develops a new set of performance measures. This latter software has been designed to take full advantage of the high resolution in the instrumentation data collected in the CTB.

The majority of these data-processing functions are performed in a highly interactive, hands-on environment with a dedicated minicomputer. This arrangement permits the flexibility and control essential to the effective utilization of sophisticated programs and engineering judgment in processing the extensive CTB instrumentation data base.

The data recorded in the CTB accumulate at a rate of approximately 25,000 words per minute. The data-processing effort outlined above is necessary, therefore, to convert this serial field data into an effective and manageable data base. The listed processing techniques organize the data into a structured, easily interpreted form. The specific data structure selected for that purpose is based on a geographic grid, which easily accommodates graphic displays of results and aids the final engineering-level performance evaluations.

The data-processing tasks that precede and are basic to generating, managing, and analyzing the CTB data base are enumerated below.

### *7.1 Data validation*

The first data-processing function, preliminary even to data validation, is performed in the field: Calibration references are generated for the instrumentation receivers, signal amplitude samples are real-time averaged, and true vehicle location data are recorded and merged with measurement results. The data are collected at the CCM and written on a common digital tape for further processing in the CTB minicomputer-based facility.

The minicomputer facility (Fig. 14) is used for many preliminary processing functions. First, each field tape is verified by self-checking/plotting routines. The verification process identifies and isolates equipment and operational software faults that occurred during data acquisition. The validated data are also inspected at this time to flag specific performance characteristics that may prove useful in analysis and interpretation.

Figure 15 shows a typical plot generated during the verification process. The figure includes six distinct types of recorded parameters, described below:

(*i*) Average power. The data for average power are displayed as a time series, with each one-half-second average value individ-

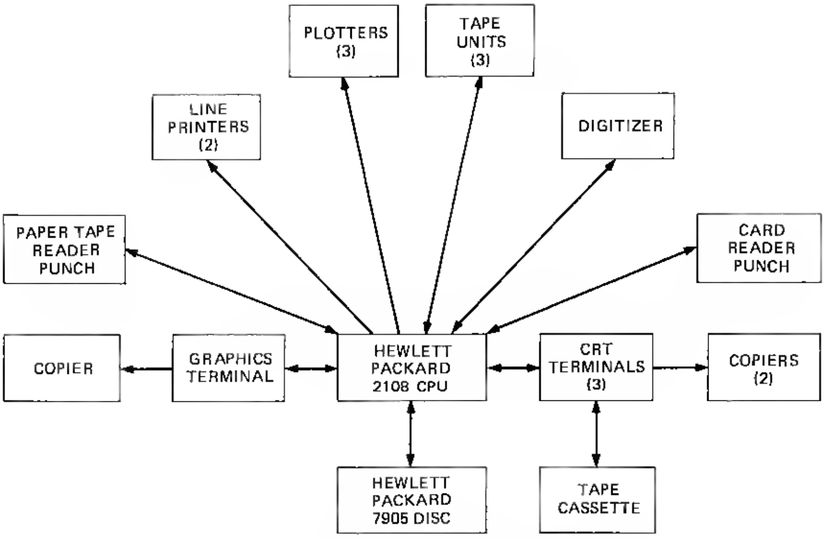


Fig. 14—Data Analysis Laboratory configuration.

ually plotted in dBm on a time axis scaled to 100 seconds per inch. (The abscissa is labeled in "record" numbers, where one record corresponds to a one-half-second data frame.) Traces 1 and 2 represent the averages for two of the three CTB cell site signals and trace 3 for the environmental noise data.

(*ii*) Peak noise. The data for peak noise, plotted as trace 4, represent a weighted mean of the field-recorded threshold counts derived from a peak-detecting circuit. The equivalent average power of the noise peaks is plotted to the same scale as the other power data.

(*iii*) Normalized signal variance. This variance, trace 5, characterizes the randomness of the transmission path. It is formed by calculating the one-half-second (256-sample) standard deviation for the power distribution and normalizing it to the mean value estimated over the same time period. A value of 1 corresponds to the Rayleigh distribution, while values in the range of 1 to 0 indicate Rician distributions with varying ratios of specular to random components.

(*iv*) Trace 6 plots vehicle relative motion; its slope indicates speed. A 27.5-mph speed corresponds to a slope running on a diagonal across the page.

(*v*) Location markers. The "major markers," which are inserted during data collection to provide coordinate references, appear as tick marks at the top of Fig. 15. Location marks and record numbers are used to isolate the data sections of operational faults and remove them from further processing.

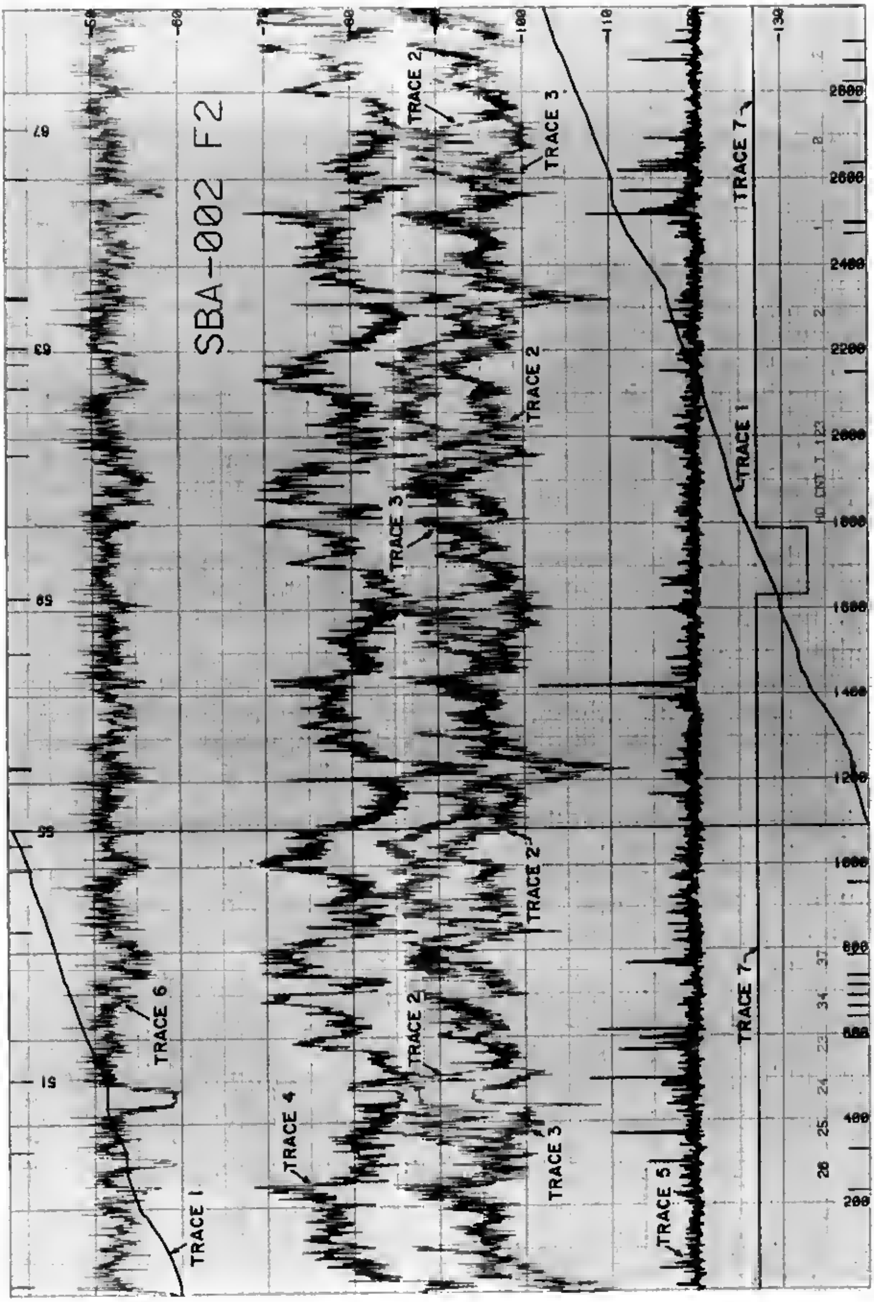


Fig. 15—Typical verification graph.

(*vi*) System trouble flags. The system flags, which are inserted by CTB operational software to identify system faults, appear as tick marks at the bottom of Fig. 15.

### *7.2 Data reduction*

Data reduction indiscriminately converts all valid bulk field data to a form suitable for more complete selective processing. In data reduction, the normalized and compressed field-recorded data, which were efficiently packed for transmission over the telemetry link and arranged to expedite live data handling, are converted to engineering units and reformatted for more straightforward manipulation in subsequent statistical calculations.

Also, during data reduction, the field-entered absolute location reference markers are converted into true geodetic coordinates. The "digitized" coordinate data are also validated before further use through a microfilm plot, generated under computer control, whicb describes the vehicle's route. The microfilm is projected to produce an overlay on an original map trace which has been used to lay out the test route; it thus confirms the validity of the position information. One such route trace generated on the STARE system is shown in Fig. 16. The numbers alongside the marked route denote field-recorded major markers.

Following route validation, field-measured data and digitized coordinate data are consolidated to associate the proper geodetic coordinates with each data entry. The combined data can then be used by higher-level data-processing programs to yield performance interpretations.

### *7.3 Performance evaluation*

The validated, reduced data are organized into a geographically defined grid structure and consolidated to facilitate analysis and inter-

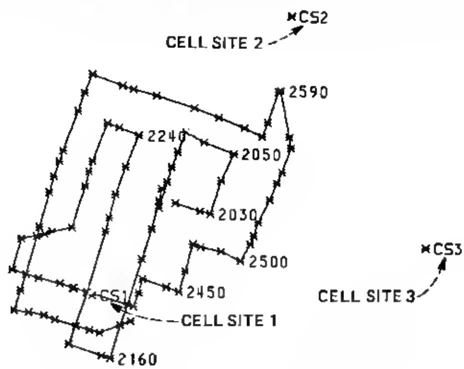


Fig. 16—Route trace on STARE system.

pı.ıtation. For this purpose, data collected in the measurement area of primary interest (a 28-square-mile circular region centered on the main cell) are subdivided into an array based on the MCL's position at the time the measurements were recorded. Such data organization is desirable because it lends itself to a straightforward evaluation of many significant system performance parameters. Handoff locations, signal amplitude distributions, and cell site service zones are typical performance parameters that are most directly described in a spatial representation. The location data supplied by the MCL accurately position the vehicle within tens of feet of its actual location and allow for such a data organization.

The principal area of interest in performance evaluations is circumscribed by the central cell's boundary. This area is subdivided into small square regions of approximately 300 feet on a side (about one city block). The outer area, extending for a distance of one radius beyond the main cell, is subdivided into regions of two different sizes, 300- and 600-ft squares, as shown in Fig. 17. This results in a data-base structure that geographically partitions the 28-square mile measurement area into about 4,500 regions. Each measurement result is identified according to the vehicle's true location at the time the data sample was collected and assigned to the appropriate small region.

The data maintained within the geographically based structure are arranged in a form to allow further processing without format conversions and time-consuming recalculations. These data are stored as accumulated running sums so that combining regions or merging data bases is accomplished by simple addition.

Table IV lists specific CTB data stored in this small-region form. Dividing the data base into 16-bit and 32-bit word formats minimizes the size of the data base while still retaining full data precision. The data in Table IV consist of system algorithm controlled events (entries 1 to 9, 16, 17, 24), propagation measurement results (entries 25 to 40), performance delineators (entries 10 to 15, 18, 19, 21 to 23), and a sum-distance-traveled entry (20). The symbols in the table are defined as follows:

$$
\begin{aligned}
\overline{S_s} &= \text{mean value of serving signal}\\
\overline{S_m} &= \text{mean value of maximum signal}\\
\overline{N} &= \text{mean value of environmental noise}\\
\overline{I} &= \text{mean value of interfering signal}\\
\overline{N_p} &= \text{mean value of weighted peak noise}\\
X, Y &= \text{preset threshold levels.}
\end{aligned}
$$

The "maximum signal" is the maximum of the three cell site signals received by the mobile; it represents the upper bound on system performance as determined by signal amplitude. This upper bound

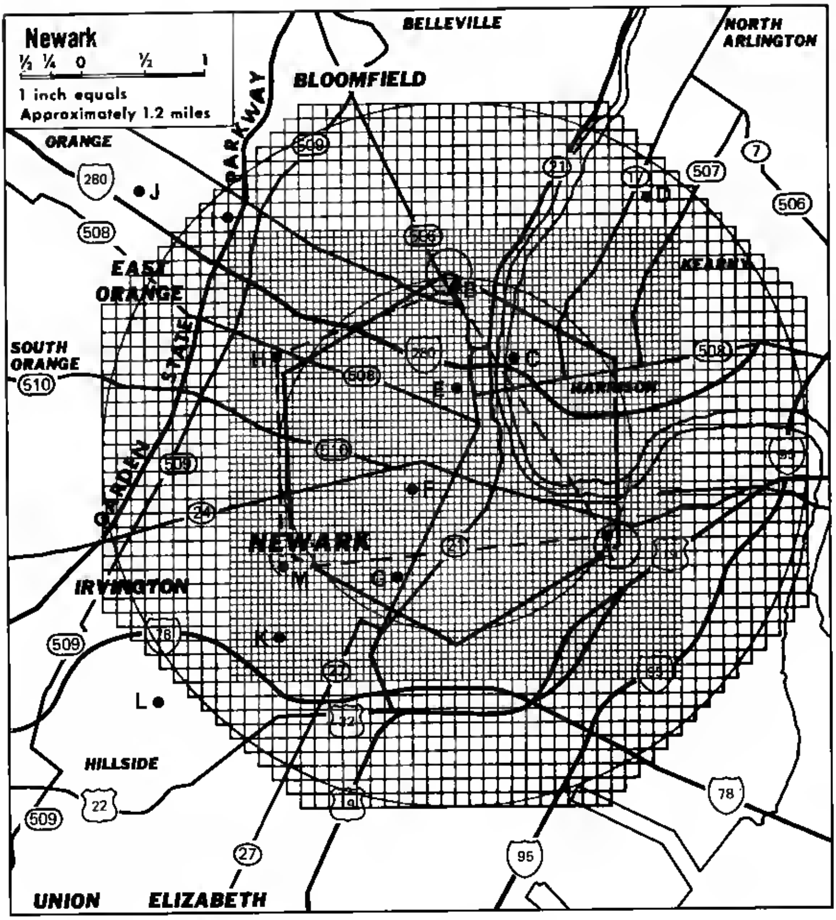


Fig. 17—Small grid binning structure.

Table IV—Information stored by region

| 16-Bit Words | | 32-Bit Words |
|---|---|---|
| 1 to 3 | Number served by cell site | 25 $\sum \overline{S}_s$ |
| 4 to 9 | Number served by cell site face | 26 $\sum (\overline{S}_s)^2$ |
| 10 to 12 | Number $\overline{S}_s/\overline{N} < (X, X \pm 2)$ dB | 27 $\sum \overline{N}$ |
| 13 to 15 | Number $\overline{S}_s/\overline{I+N} < (Y, Y \pm 2)$ dB | 28 $\sum (\overline{N})^2$ |
| 16 | Number of handoffs intercell | 29 $\sum \overline{N}_p$ |
| 17 | Number of handoffs intracell | 30 $\sum (\overline{N}_p)^2$ |
| 18 | Number $\overline{S}_m/\overline{N} < X$ dB | 31 $\sum \overline{S}_m$ |
| 19 | Number $\overline{S}_m/\overline{I+N} < Y$ dB | 32 $\sum (\overline{S}_m)^2$ |
| 20 | $\sum$ Distance | 33 $\sum \overline{I}$ |
| 21 to 23 | Number of signaling errors by cell site | 34 $\sum (\overline{I})^2$ |
| 24 | Number of nonstandard terminations | 35 $\sum \{\overline{S}_s * \text{Distance}\}$ |
| | | 36 $\sum \{(\overline{S}_s)^2 * \text{Distance}\}$ |
| | | 37 $\sum \{\overline{S}_m * \text{Distance}\}$ |
| | | 38 $\sum \{(\overline{S}_m)^2 * \text{Distance}\}$ |
| | | 39 $\sum \{\overline{I} * \text{Distance}\}$ |
| | | 40 $\sum \{(\overline{I})^2 * \text{Distance}\}$ |

serves as a reference point for comparing the results of different algorithms.

Certain system performance evaluations have the greatest significance when displayed in a velocity-independent form. To obtain such results, the data collected while the mobile is stopped or moving slowly must be appropriately weighted. As an example, the one-half-second averaged signal amplitude is not a valid indicator of the mean local field strength at slow speeds. Velocity weighting (entries 35 to 40 of Table IV) preserves the distance dependence in the results while providing unbiased signal mean estimates.

Table V lists some of the results directly available from the data stored for each region. The data include statistical descriptors of signal strength and performance measures expressed as percentages of the total data collected within each region. Such data are available for each of the 4,500 small regions.

Further processing of the preliminary results develops outputs in a form suitable for specific performance evaluations. For these, graphic displays are most useful since they take advantage of the inherent ability of the human eye to sort quickly through large quantities of pattern data. Because of the geographic grid arrangement of data, it is a relatively straightforward task to develop graphic output in the form of "shade plots" of the desired information. In shade plots, the expected range of each variable is divided into a number of bands, each of which is represented by a unique shade of gray and plotted in an $x$-$y$ grid.

A shade plot using the data generated from propagation rules developed from earlier field measurements is shown in Fig. 18. The algorithm that is used accounts for antenna height and gain (not all equal in this example) and calculates the signal level within each small region for each of the three cell sites with an assumed 10 watts of power delivered to the antenna terminals at each site. The maximum signal strength determined for each region is then plotted. Although this specific example produces a particularly symmetric result because of the idealized assumptions, the utility of this technique is apparent.

Figure 18 is an example of one general category of performance results. Conventional statistical data-processing techniques extend

Table V—Derived performance results

| | |
|---|---|
| 1. | Mean and standard deviation $S_s$, $N$, $S_m$, $I$, $N_p$ |
| 2. | $\overline{S}_s/\overline{N} < (X, X \pm 2)$ dB (percent*) |
| 3. | $\overline{S}_s/\overline{I+N} < (Y, Y \pm 2)$ dB (percent) |
| 4. | $\overline{S}_m/\overline{N} < X$ dB (percent) |
| 5. | $\overline{S}_m/\overline{I+N} < Y$ dB (percent) |
| 6. | Service by cell site (percent) |
| 7. | Service by face (percent) |
| 8. | Mean and standard deviation $S_s'$, $S_m'$, $I'$ (prime denotes distance weighting) |

* All percentages are normalized to total number of ½-second records within each region.

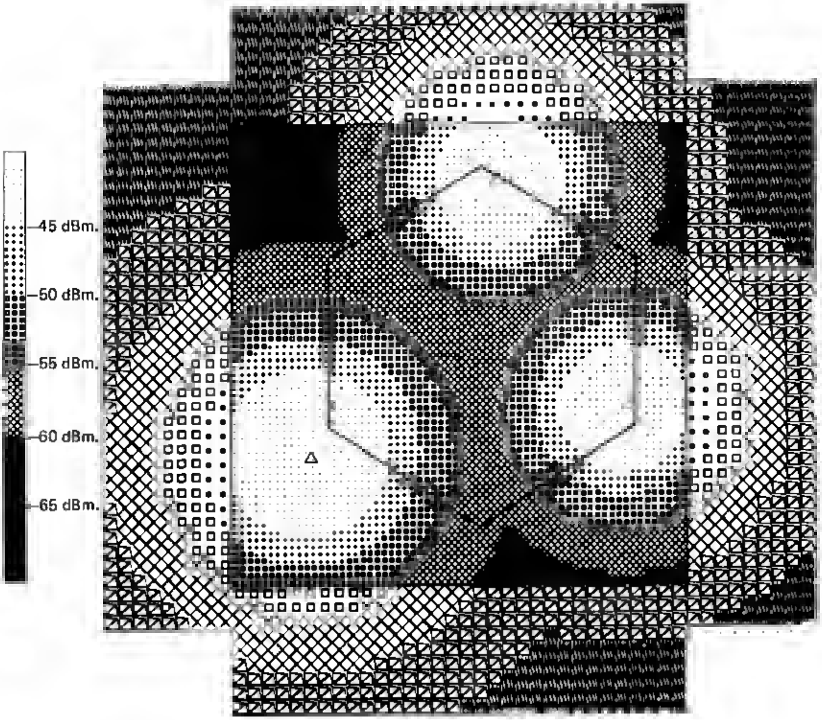


Fig. 18—Typical shade plot.

such shade plot characterizations to specific performance evaluations. In addition, a performance summary is calculated for each measurement run as the data are processed to the small-region form. The results (Table VI) provide a quick-look system-level overview, which can be compared with premeasurement expectations to gauge how the tests are progressing.

### *7.4 Real-time simulation*

The real-time simulation software supplies a field-like operational capability in the data analysis laboratory. Because of the microscopic resolution with which the CTB signals and operations are monitored and recorded by the field instrumentation, field data can be reprocessed in the laboratory much the way they are processed by the system controller at the time of data collection.

In the simulations, the system operating algorithms can be modified easily to study the effects of proposed changes on the resulting system performance. The real-time simulations, operating on the identical instrumentation data used by the system controller in the field, generate outputs that can be used by the same analysis routines used to

process standard field data. In this manner, much of the time and cost penalties associated with field operations can be avoided as various alternative engineering solutions are explored. Once an apparently satisfactory modification is obtained, this result is confirmed through a final "live" evaluation of the new algorithm in the field.

In performing the simulations, the user can select for reprocessing specific data segments that represent spatial or time-based portions of the field-recorded data of particular interest. These data segments can be submitted to an array of algorithm and parameter modifications to test their influence on system performance while the initial system state (serving cell site, antenna, power, etc.) is user-specified or forced to duplicate the configuration that existed at the time the field data were observed. These techniques permit quick-turnaround iterations to isolate observed problems rapidly and to develop proven solutions.

Table VII lists examples of intermediate results that can be calculated and selected for display while the simulations are being performed. The data provide on-line feedback concerning the success of

Table VI—Tabulated performance results

| | |
|---|---|
| Percent of area included in data base | |
| Total run time | |
| Total distance traveled | |
| Average velocity | |
| Total number of intercell handoffs | |
| Total number of intracell handoffs | |
| Probability of intercell handoff | |
| Probability of intracell handoff | |
| Total number of nonstandard terminations | |
| Total number of signaling errors by cell site | |
| Percent of time mobile was served by face and cell site | |
| **Histograms** | |
| $\overline{S}_s/\overline{N}$ | 5 to 30 dB |
| $\overline{S}_m/\overline{N}$ | 5 to 30 dB |
| $\overline{S}_s/\overline{I+N}$ | 4 to 29 dB |
| $\overline{S}_m/\overline{I+N}$ | 4 to 29 dB |
| $\Delta(\overline{S}_s/\overline{N})$ | −30 to +30 dB |
| $\Delta(\overline{S}_s/\overline{I+N})$ | −30 to +30 dB |
| Time to first handoff | 5 to 90 seconds |
| Time between subsequent handoffs | 5 to 90 seconds |

Table VII—Intermediate display options

| |
|---|
| Total time of run |
| Number of records processed |
| Total number of calls processed |
| Number of handoffs per call |
| Number of degraded calls |
| Number of locating data requests from serving and nonserving cell sites |
| Number of times locating signals are below secondary threshold while average serving signal is above degraded call level |
| Number of lost mobiles |
| Number of times trouble flag is set on requested data |
| Numbers and types of handoffs |
| Percent of time mobile is served by each cell site (and face) |

the modifications and guide the choice of alternative solutions. The much more complete and laborious analysis processing is thus bypassed until viable solutions have been isolated. The combination of direct feedback during the simulations plus full analysis of final results assures a high success rate when the proposed solutions finally undergo field evaluation in the live system.

## VIII. ACKNOWLEDGMENTS

Most major projects represent the efforts of many people. Such is the case with the Cellular Test Bed. The authors, in documenting the CTB, have merged the contributions of all members of the Mobile Telephone Field Studies Department. Their dedication and hard work are gratefully acknowledged.